

## A very bright $i = 16.44$ quasar in the ‘redshift desert’ discovered by LAMOST

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**Abstract** The redshift range from 2.2 to 3, is known as the ‘redshift desert’ of quasars because quasars with redshift in this range have similar optical colors as normal stars and are thus difficult to be found in optical sky surveys. A quasar candidate, SDSS J085543.40-001517.7, which was selected by a recently proposed criterion involving near-IR  $Y - K$  and optical  $g - z$  colors, was identified spectroscopically as a new quasar with redshift of 2.427 by the LAMOST commissioning observation in December 2009 and confirmed by the observation made with the NAOC/Xinglong 2.16m telescope in March 2010. This quasar was not targeted in the SDSS spectroscopic survey because it locates in the stellar locus of the optical color-color diagrams, while it is clearly separated from stars in the  $Y - K$  vs.  $g - z$  diagram. Comparing with other SDSS quasars we found this new quasar with  $i$  magnitude of 16.44 is apparently the brightest one in the redshift range from 2.3 to 2.7. From the spectral properties we derived its central black hole mass as  $(1.4 \sim 3.9) \times 10^{10} M_{\odot}$  and the bolometric luminosity as  $3.7 \times 10^{48} \text{ erg s}^{-1}$ , which indicates that this new quasar is intrinsically very bright and belongs to the most luminous quasars in the universe. Our identification supports that quasars in the redshift desert can be found by the quasar selection criterion involving the near-IR colors. More missing quasars are expected to be recovered by the future LAMOST spectroscopic surveys, which is important to the study of the cosmological evolution of quasars at redshift higher than 2.2.

**Key words:** quasars: general — quasars: emission lines — galaxies: active

## 1 INTRODUCTION

After the discovery of first quasar (Schmidt 1963), many quasar surveys have been carried out in optical band and the number of quasars has increased steadily in the past four decades (Richards et al. 2009). Especially, a large number of quasars have been discovered in two recent spectroscopic surveys, namely, the Two-Degree Fields (2DF) survey (Boyle et al. 2000) and Sloan Digital Sky Survey (SDSS) (York et

al. 2000). 2DF has discovered more than 20,000 quasars (Croom et al. 2004), and SDSS has identified more than 100,000 quasars (Schneider et al. 2010; Abazajian et al. 2009). 2DF mainly selected lower redshift ( $z < 2.2$ ) quasars with UV-excess (Smith et al. 2005), while SDSS adopted a multi-band optical color selection method for quasars mainly by excluding the point sources in the stellar locus of color-color diagrams (Richards et al. 2002). Some dedicated methods were also proposed for finding high redshift quasars (Fan et al. 2001a,b; Richards et al. 2002). However, the efficiency of identifying quasars with redshift between 2.2 and 3 is obviously low in SDSS (Schneider et al. 2010), because quasars with such redshift usually have similar optical colors as stars and are thus mostly excluded by the SDSS quasar candidate selection algorithm. Therefore, the redshift range from 2.2 to 3 is often regarded as the ‘redshift desert’ of quasars because of the difficulty in identifying quasars within this redshift range.

In addition, the low efficiency of finding quasars with redshift between 2.2 and 3 has led to the obvious incompleteness of quasar sample in this redshift range and serious problems in constructing the luminosity function for quasars. More importantly, many studies have shown that the quasar activity actually peaks at redshift range  $2 < z < 3$  (see Richards et al. 2006; Jiang et al. 2006). Therefore, recovering the missing quasars with redshift between 2.2 and 3 has become an important task in the quasar study.

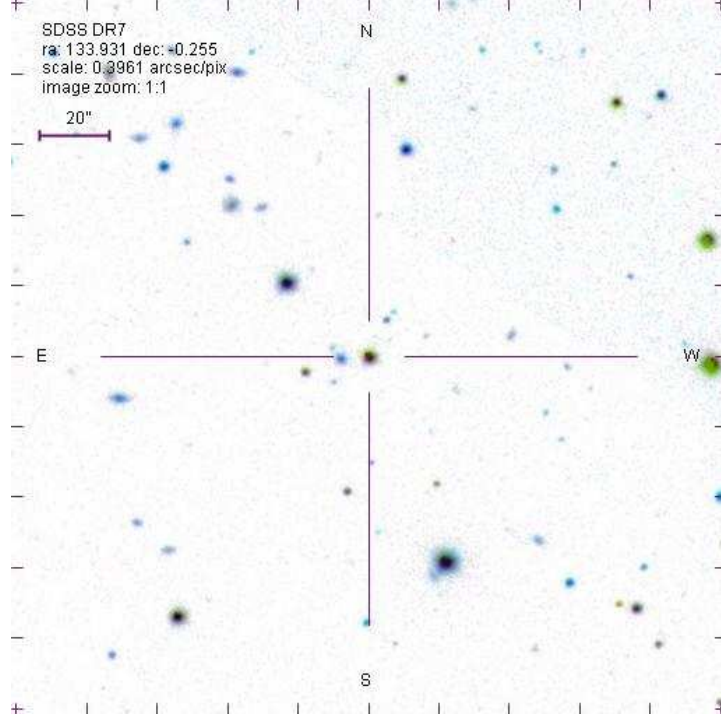
Although quasars in the redshift desert have similar optical colors as stars, they are usually more luminous than normal stars in the infrared K-band because the fluxes of normal stars decreases rapidly in the near-IR bands while quasar SEDs are relatively flat (Warren et al. 2000). An important way of finding these missing quasars has been suggested by using the infrared K-band excess based on the UKIRT (UK Infrared Telescope) Infrared Deep Sky Survey (UKIDSS) (Warren et al. 2000; Hewett et al. 2006; Maddox et al. 2008). Combining the UKIDSS  $YJHK$  and SDSS  $ugriz$  magnitudes, some criteria to separate quasars and stars have been proposed previously. Maddox et al. (2008) suggested a selection criterion of  $z < 4$  quasar candidates in the  $g - J$  vs.  $J - K$  diagram. Chiu et al. (2007) investigated the different color-color diagrams in optical and near-IR bands with a sample of 2837 SDSS-UKIDSS quasars, and found that the  $g - r$  vs.  $u - g$  diagram and the  $H - K$  vs.  $J - H$  diagram are more effective in separating quasars and stars than other diagrams. They also proposed to use the  $Y - K$  vs.  $u - z$  diagram to select low redshift ( $z < 3$ ) quasars. Recently, based on a SDSS-UKIDSS sample of 8498 quasars, Wu & Jia (2010) proposed to use the  $Y - K$  vs.  $g - z$  diagram to select  $z < 4$  quasars and use the  $J - K$  vs.  $i - Y$  diagram to select  $z < 5$  quasars. Although with these two criteria we can recover 8447 of 8498 SDSS-UKIDSS quasars (with a percentage of 99.4%), we still need to demonstrate whether we can efficiently discover new quasars, especially those in the redshift desert, by applying our criteria to select quasar candidates in the SDSS spectroscopically surveyed area.

The Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) is a 4-meter reflecting Schmidt telescope with 20 square degree field of view (FOV) and 4000 fibers in the focal plane (Su et al. 1998), located in the NAOC/Xinglong station. After finishing its main construction in 2008, LAMOST has entered the commissioning phase since 2009. Some test observations have been done in the winter of 2009. Although LAMOST has not reach its full capability in the commissioning phase, these observations already led to the discovery of some new quasars, including a bright quasar with redshift of 2.427, which is the first quasar in the ‘redshift desert’ discovered by LAMOST.

## 2 TARGET SELECTION AND OBSERVATION

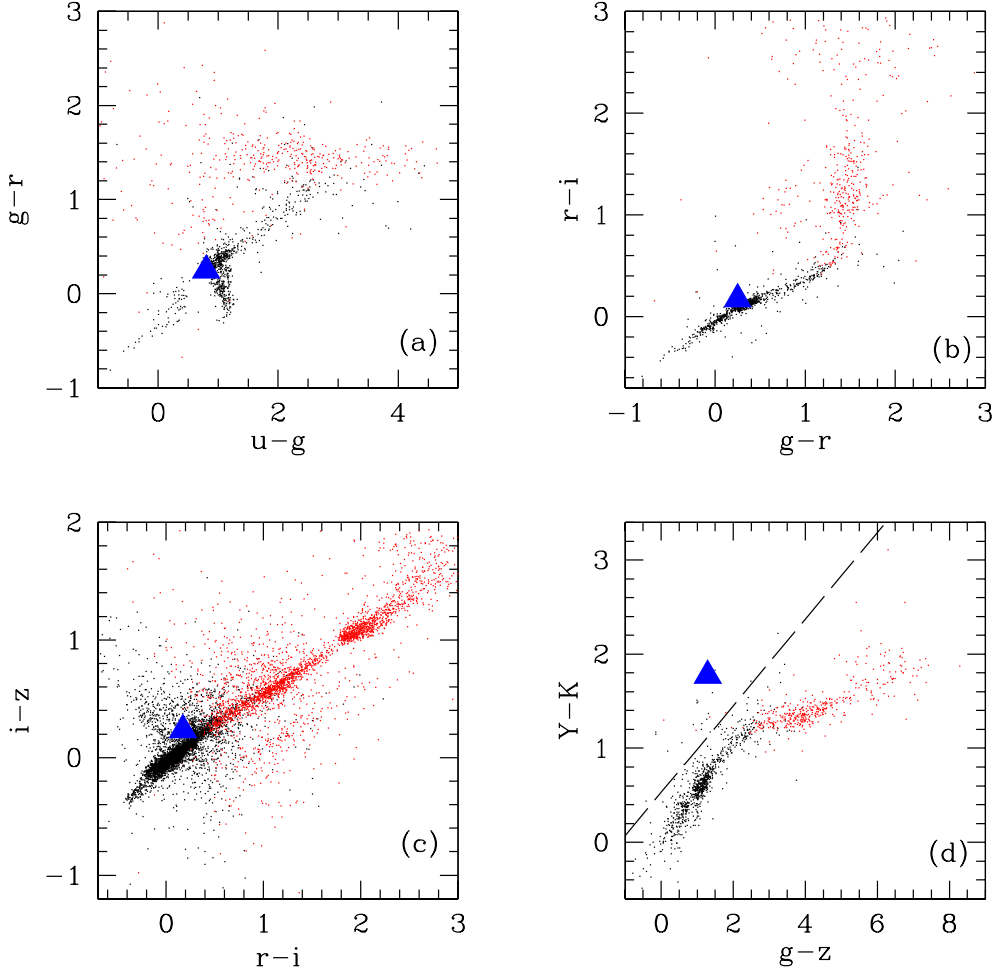
In order to test whether our newly proposed quasar selection criterion in the  $Y - K$  vs.  $g - z$  diagram is efficient in identifying quasars, we selected many candidates in several sky fields overlapped between UKIDSS and SDSS survey area with RA from 0 to 9 hours for the LAMOST commissioning observations in the winter of 2009. Although LAMOST has met many problems during these commissioning observations, such as the low accuracy of fiber positioning and poor dom seeing condition, we were still able to identify some new quasars including one reported here.

SDSS J085543.40-001517.7 is a relatively bright source among our quasar candidates. After the correction of Galactic extinction using the map of Schlegel et al. (1998), Its SDSS  $ugriz$  magnitudes (in AB system) are 17.67, 16.87, 16.62, 16.44, 16.20, respectively and its UKIDSS



**Fig. 1** The finding chart of SDSS J085543.40-001517.7. The size is  $200'' \times 200''$ .

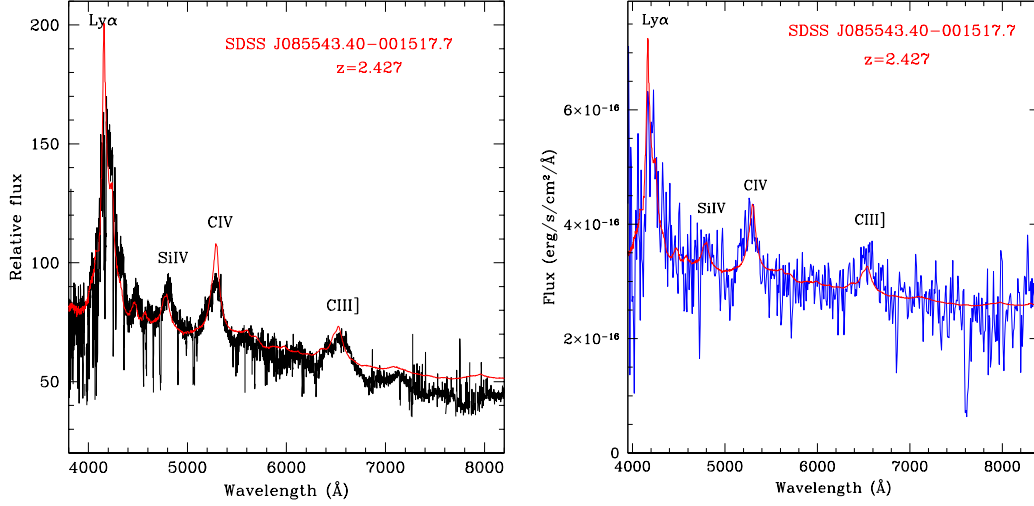
$YJHK$  magnitudes (in Vega system) are 15.61, 15.24, 14.60, 13.84, respectively. The offset between its SDSS and UKIDSS positions is  $0.05''$ . Fig. 1 shows its SDSS finding chart (obtained from <http://cas.sdss.org/dr7/en/tools/chart/chart.asp>). Obviously SDSS J085543.40-001517.7 is a bright point source, surrounded by several other fainter sources with offsets from  $8''$  to  $20''$ . In Fig. 2 we show the location of this source in 3 optical color-color diagrams and the  $Y - K$  vs.  $g - z$  diagram, in comparison with the 8996 SDSS-UKIDSS stars (Wu & Jia 2010). Note that in the  $Y - K$  vs.  $g - z$  diagram the magnitude of  $g$  and  $z$  have been converted to the magnitudes in Vega system by using the scalings (Hewett et al. 2006):  $g = g(AB) + 0.103$  and  $z = z(AB) - 0.533$ . It is clear that SDSS J085543.40-001517.7 locates in the stellar locus in three optical color-color diagrams, but is well separated from



**Fig. 2** The location of SDSS J085543.40-001517.7 (blue triangle) in three optical color-color diagrams (a,b,c) and the  $Y - K$  vs.  $g - z$  diagram (d), in comparing with the 8996 SDSS-UKIDSS stars. Black and red dots represent the normal and later type stars, respectively. Dashed line shows the  $z < 4$  quasar selection criterion proposed by Wu & Jia (2010).

stars in the  $Y - K$  vs.  $g - z$  diagram and meets the selection criterion,  $Y - K > 0.46 * (g - z) + 0.53$ , proposed by Wu & Jia (2010). This also explains why this source was not selected as a quasar candidate in SDSS, although it is bright enough.

The spectroscopy of SDSS J085543.40-001517.7 was obtained by LAMOST during the commissioning observations on December 18, 2009, with the spectral resolution of  $R \sim 1000$  and the exposure time of 30 minutes. The spectrum was processed using a preliminary version of LAMOST spectral pipeline. In the left panel of Fig. 3 we show the LAMOST spectrum of SDSS J085543.40-001517.7 (some sky light emissions were not well subtracted). From the spectrum we can clearly observe at least four strong emission lines, namely,  $\text{Ly}\alpha$   $\lambda 1216$ ,  $\text{Si IV } \lambda 1400$ ,  $\text{C IV } \lambda 1549$  and  $\text{C III] } \lambda 1909$ . With these four lines we derived an average redshift of  $z = 2.427$  for this new quasar. Three weak emission lines,



**Fig. 3** Left panel: The LAMOST spectrum of SDSS J085543.40-001517.7. Right panel: The spectrum of SDSS J085543.40-001517.7 taken by the NAO/Xinglong 2.16m telescope. The scaled SDSS composite quasar spectrum (in red color) is shown for comparison.

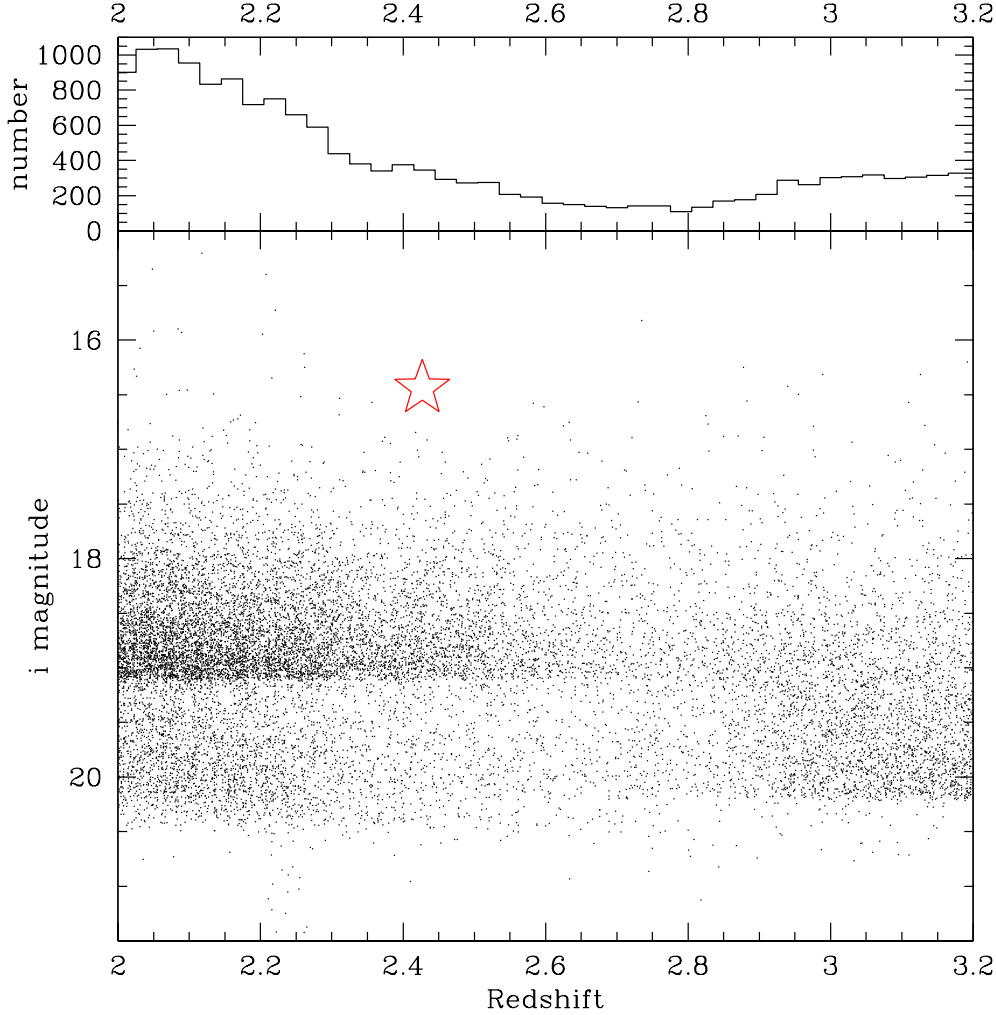
N V  $\lambda 1240$ , O I  $\lambda 1304$  and C II  $\lambda 1335$ , can be also seen between Ly $\alpha$  and Si IV lines. The complicated feature around  $5900\text{\AA}$  is due to the problem in combining the LAMOST blue and red spectra, which overlap with each other from  $5700\text{\AA}$  to  $6000\text{\AA}$ . In this figure we also compare the LAMOST spectrum with the scaled SDSS composite quasar spectrum (Vanden Berk et al. 2001). It is clearly that both match well with each other, except in the red end.

On March 9, 2010, we also used the NAO/Xinglong 2.16m telescope to do spectroscopy of this new quasar. Because the seeing condition was bad ( $4''$ - $5''$ ), we took two 40-minute exposures on this quasar and obtained the median spectrum, which is shown in the right panel of Fig. 3 in comparison with the scaled SDSS composite quasar spectrum. Although its signal to noise ratio is lower than the LAMOST spectrum, four strong emission lines can still be clearly observed. Moreover, its continuum shape matches the SDSS composite quasar spectrum better than the LAMOST spectrum, especially in the red end.

### 3 PROPERTIES OF SDSS J085543.40-001517.7

With the  $i$  magnitude of 16.44 and redshift of 2.427, SDSS J085543.40-001517.7 is undoubtedly a very bright quasar. We compared it with other SDSS quasars in the redshift range from 2 to 3.2 and found the new quasar is indeed very bright. In Fig. 4 we show the location of the new quasar in the magnitude-redshift diagram in comparison with other SDSS quasars, as well as the histogram of the redshift distribution of SDSS quasars. The redshift distribution clearly shows the presence of ‘redshift desert’ in the redshift range from 2.2 to 3. The new quasar is apparently the brightest one in the redshift range from 2.3 to 2.7. Its absolute  $i$  magnitude is -30.0 if the cosmological parameters  $H_0=70 \text{ km s}^{-1}\text{Mpc}^{-1}$ ,  $\Omega_M = 0.3$  and  $\Omega_\Lambda = 0.7$  are adopted. Clearly this quasar belongs to the most luminous quasars in the universe.

We also searched the counterparts of SDSS J085543.40-001517.7 in other wavelength bands. From the VLA/FIRST radio catalog (White et al. 1997) we did not find any radio counterpart within  $20''$  from its SDSS position. The closest radio source is  $121.5''$  far away. Therefore, this quasar is a radio-quiet one, which is also another reason why it is missed by the SDSS spectroscopy. We also searched



**Fig. 4** The location of SDSS J085543.40-001517.7 (red star) in the magnitude-redshift diagram in comparison with the SDSS DR7 quasars in redshift range from 2 to 3.2. The redshift distribution of SDSS quasars is also shown in the upper panel, in which the redshift desert (with redshift from 2.2 to 3) is clearly presented.

the ROSAT X-ray source catalog (Voges et al. 1999) and did not find any counterpart within  $1'$ . The closest X-ray source is  $23'$  away. From GALEX catalog (Morrissey et al, 2007) we failed to find any ultraviolet counterpart within  $5''$ . One GALEX source is  $27''$  away (in the south-western direction) from the optical position of SDSS J085543.40-001517.7, and is clearly the counterpart of another fainter extended source in the SDSS image. Therefore, we believe that SDSS J085543.40-001517.7 is faint in radio, UV and X-ray bands, although it is very luminous in optical and near-IR bands.

From the spectral properties we can estimate the black hole mass and bolometric luminosity of this new quasar. After doing the redshift correction, Galactic extinction correction using the reddening map of Schelegal et al. (1998), continuum fitting and Fe II subtraction using the template from Vestergaard & Wilkes (2001), we measured the C IV line width (FWHM, the Full Width at Half Maximum) and the



rest frame  $1350\text{\AA}$  continuum flux from the spectrum. Because we did not make the absolute flux calibration of the LAMOST spectrum of SDSS J085543.40-001517.7, we used the ultraviolet continuum window  $1320\text{\AA} - 1330\text{\AA}$  to calibrate the LAMOST spectrum with the spectrum taken by the 2.16m telescope. The C IV FWHM values measured from the LAMOST and 2.16m spectra are  $8520\text{km s}^{-1}$  and  $11040\text{km s}^{-1}$ , respectively. Due to the lower signal to noise ratio of the 2.16m spectrum (see the right panel of Fig. 3), we took the C IV FWHM value from the LAMOST spectrum in the following calculation. The black hole mass estimation was done with two similar formula proposed by Kong et al. (2006) and Vestergaard & Peterson (2006), both involving the C IV line width and  $1350\text{\AA}$  continuum luminosity. The first one gives  $M_{BH} = 1.4 \times 10^{10} M_{\odot}$  and the latter one gives  $M_{BH} = 3.9 \times 10^{10} M_{\odot}$ . Using a scaling between  $1350\text{\AA}$  luminosity and bolometric luminosity,  $L_{bol} = 4.62 L_{1350}$ , given by Vestergaard (2004) based on the SED of radio-quiet quasars (Elvis et al. 1994), we estimated the bolometric luminosity of this new quasar as  $3.7 \times 10^{48} \text{erg s}^{-1}$ , which is about  $(0.5 \sim 1.4)$  times of the Eddington luminosity if the above estimated black hole mass is adopted. Obviously, this quasar is intrinsically very bright, and is accreting matters with the accretion rate around the Eddington limit.

#### 4 DISCUSSION

Quasars with redshifts in the range from 2.2 to 3 are very important for studying their cosmological evolution, and the relation between quasar activity and star formation activity which peaks at redshift between 1 and 2 (Madau et al. 1998). However, because these quasars have similar optical colors as normal stars, it is very difficult for find them in previous quasar surveys. The low efficiency of finding quasars in the ‘redshift desert’ has led to the obvious incompleteness of quasar sample in this redshift range and serious problems in constructing the luminosity function for quasars around the redshift peak (between 2 and 3) of quasar activity (Richards et al. 2006; Jiang et al. 2006).

In this paper we have presented a case study to find a very bright new quasar in the redshift desert by the LAMOST commissioning observation. The spectroscopic identification of an  $i = 16.44$  source, SDSS J085543.40-001517.7, as a  $z = 2.427$  quasar gives us confidence to discover more missing quasars in the future LAMOST quasar survey. This discovery also supports the idea that by combining the UKIDSS near-IR colors with the SDSS optical colors we are able to efficiently recover these missing quasars. In the winter of 2009, LAMOST has made test observations on several sky fields and we are now searching for more quasars from the spectra taken in these fields. The discovery of more new quasars in these fields will be reported in the future works. We hope that in the next a few months great progress will be made in improving the capability of LAMOST spectroscopy and the spectral processing pipeline. As long as LAMOST can reach its designed capability after the commissioning phase, we expect to find several hundred-thousands of quasars in the LAMOST quasar survey. This will form the largest quasar sample in the world and play a leading role in the quasar study of the next decade.

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